Leptonic CP Measurement
&
New Physics Alternatives

Shao-Feng Ge

(gesf@sjtu.edu.cn)

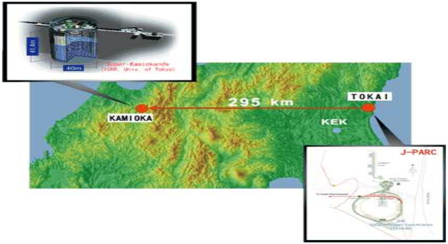
Tsung-Dao Lee Institute (TDLI-SJTU)

2019-10-9

Jarah Evslin, **SFG**, Kaoru Hagiwara, JHEP **1602** (2016) 137 [arXiv:1506.05023]
SFG, Pedro Pasquini, M. Tortola, J. W. F. Valle, PRD **95** (2017) No.3, 033005 [arXiv:1605.01670]
SFG, Alexei Smirnov, JHEP **1610** (2016) 138 [arXiv:1607.08513]
SFG [arXiv:1704.08518]
SFG, Stephen Parke, Phys.Rev.Lett. **122** (2019) no.21, 211801 [arXiv:1812.08376]
SFG, Hitoshi Murayama [arXiv:1904.02518]

CP Measurement @ Accelerator Exps

- T2K



- NOνA

- DUNE/T2KII/T2HK/T2HKK/T2KO; MOMENT/ADS-CI/DAEδALUS; Super-PINGU

The Dirac CP Phase δ_D @ Accelerator Exp

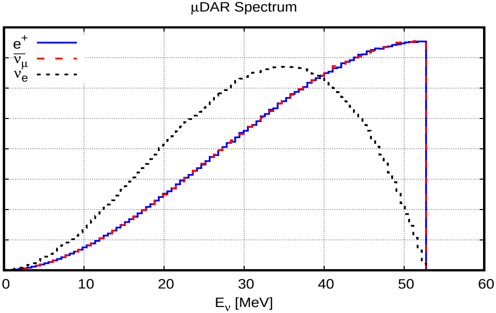
Accelerator experiment, such as **T2(H)K**, uses off-axis beam to compare ν_e & $\overline{\nu}_e$ appearance @ the oscillation maximum.

- **Disadvantages**:
  - **Efficiency**:
    - Proton accelerators produce ν more efficiently than $\overline{\nu}$ $(\sigma_\nu > \sigma_{\overline{\nu}})$.
    - The $\overline{\nu}$ mode needs more beam time $[\mathbf{T}_{\overline{\nu}} : \mathbf{T}_\nu = \mathbf{2} : \mathbf{1}]$.
    - Undercut statistics ⇒ Difficult to reduce the uncertainty.
  - **Degeneracy**:
    - Only $\sin \boldsymbol{\delta}_\mathbf{D}$ appears in $P_{\nu_\mu \to \nu_e}$ & $P_{\overline{\nu}_\mu \to \overline{\nu}_e}$.
    - Cannot distinguish $\boldsymbol{\delta}_\mathbf{D}$ from $\boldsymbol{\pi} - \boldsymbol{\delta}_\mathbf{D}$.
  - **CP Uncertainty** $\frac{\partial P_{\mu e}}{\partial \delta_D} \propto \cos \delta_D \Rightarrow \Delta(\delta_D) \propto \mathbf{1}/\cos \boldsymbol{\delta}_\mathbf{D}$.
- **Solution**:

  Measure $\overline{\nu}$ mode with μ^+ decay @ rest (μDAR)

μDAR $\bar{\nu}$ Oscillation Experiments

- A cyclotron produces 800 MeV proton beam @ fixed target.
- Produce $\pi^{\pm}$ which stops &
  - π^{-} is absorbed,
  - π^{+} decays @ rest: $\pi^{+} \rightarrow \mu^{+} + \nu_{\mu}$.
- μ^{+} stops & decays @ rest: $\boldsymbol{\mu}^{+} \rightarrow \mathbf{e}^{+} + \overline{\boldsymbol{\nu}}_{\boldsymbol{\mu}} + \boldsymbol{\nu}_{\mathbf{e}}$.

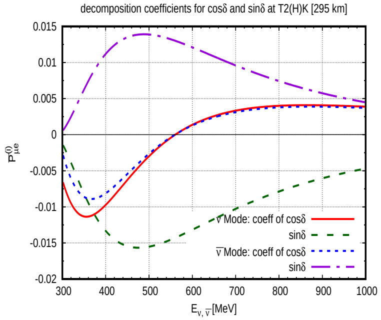


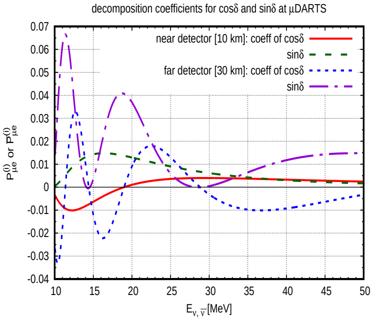
- $\overline{\nu}_{\mu}$ travel in all directions, oscillating as they go.
- A detector measures the $\overline{\nu}_e$ from **$\overline{\nu}_{\mu} \rightarrow \overline{\nu}_{e}$ oscillation**.

Accelerator + μDAR Experiments

Combining $\nu_\mu \rightarrow \nu_e$ **@ accelerator** [narrow **peak @ 550 MeV**] & $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ **@ μDAR** [wide **peak $\sim$ 45 MeV**] solves the 2 problems:

- **Efficiency**:
  - $\overline{\nu}$ @ high intensity, μDAR is plentiful enough.
  - Accelerator Exps can devote all run time to the ν mode. With same run time, the statistical uncertainty drops by $\sqrt{3}$.
- **Degeneracy**: (**decomposition in propagation basis** [1309.3176])





DAEδALUS

- It's the **FIRST** proposal along this line:
  - **3** μDAR with **3** high-intensity cyclotron complexes.
  - **1** detector.
  - Different baselines: **1.5**, **8** & **20** km to break degeneracies.
- **Disadvantages**:
  - The final-state lepton from IBD @ low energy is **isotropic**.
  - **Cannot** distinguish $\overline{\nu}_e$ from different sources
  - Baseline **cannot be measured**.
  - Cyclotrons **cannot** run simultaneously (20∼25% duty factor).
  - **Large** statistical uncertainty.
  - **Higher intensity** is necessary.
  - **Expensive** & Technically **challenging**.

New Proposals

1 μDAR source + **2** detectors

Advantages

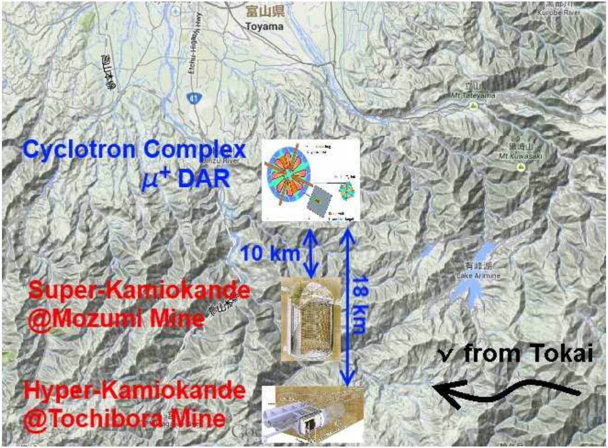
- Full (**100%**) duty factor!
- **Lower** intensity: $\sim$ **9mA** [$\sim$ **4**× lower than DAEδALUS]
- Not far beyond the current state-of-art technology of cyclotron [**2.2mA** @ Paul Scherrer Institute]
- MUCH **cheaper** & technically **easier**.
  - Only one cyclotron.
  - Lower intensity.

Disadvantage?

- A second detector!
  - **μDAR** with **T**wo **S**cintillators (**μDARTS**) [Ciuffoli, Evslin & Zhang, 1401.3977] also Smirnov, Hu, Li & Ling [1802.03677, 1808.03795]
  - **T**okai '**N** **T**oyama to(**2**) **K**amioka (**TNT2K**) [Evslin, Ge & Hagiwara, 1506.05023]

TNT2K

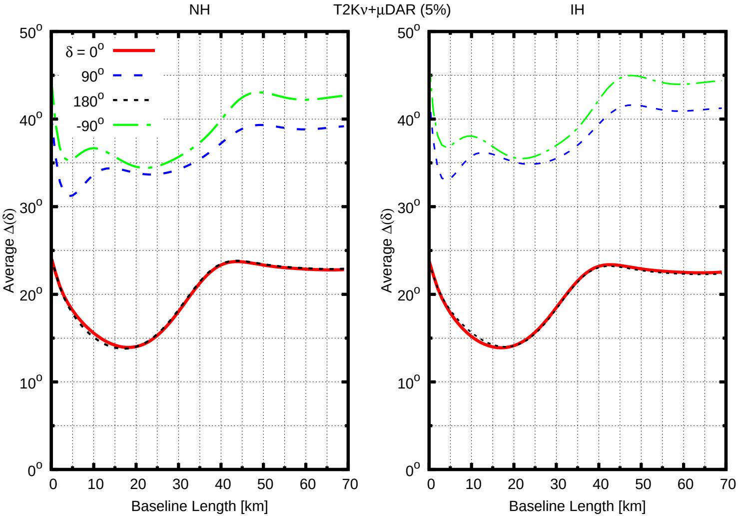
- T2(H)K + μSK + μHK



- μDAR is also useful for **material**, **medicine** industries in Toyama

δ_D Precision @ TNT2K

Evslin, Ge & Hagiwara [1506.05023]



Simulated by **NuPro**, http://nupro.hepforge.org/

δ_D Precision @ TNT2K

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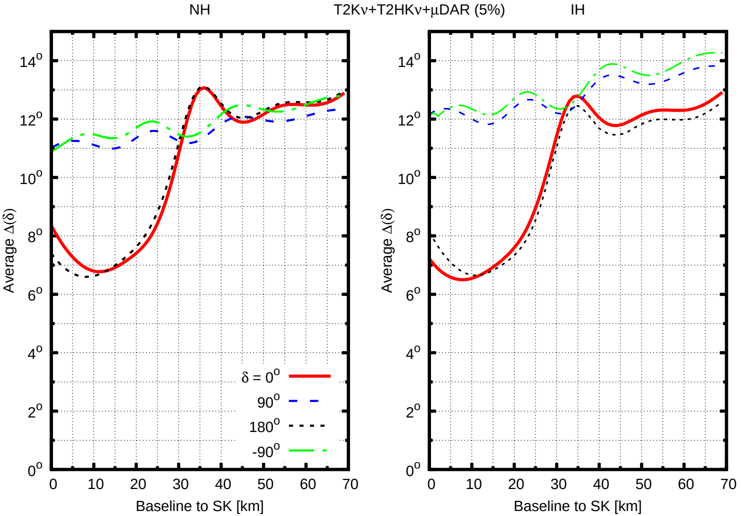


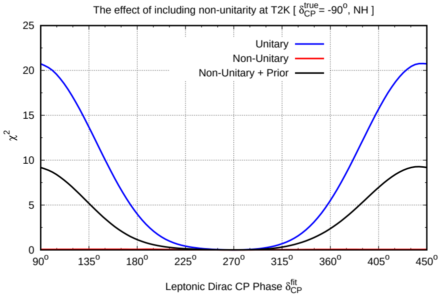
Simulated by **NuPro**, http://nupro.hepforge.org/

Non-Unitarity Mixing (NUM)

Ge, Pasquini, Tortola & Valle [1605.01670]

$$N = N^{NP} U = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ |\alpha_{21}| e^{i\phi} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} U \,.$$

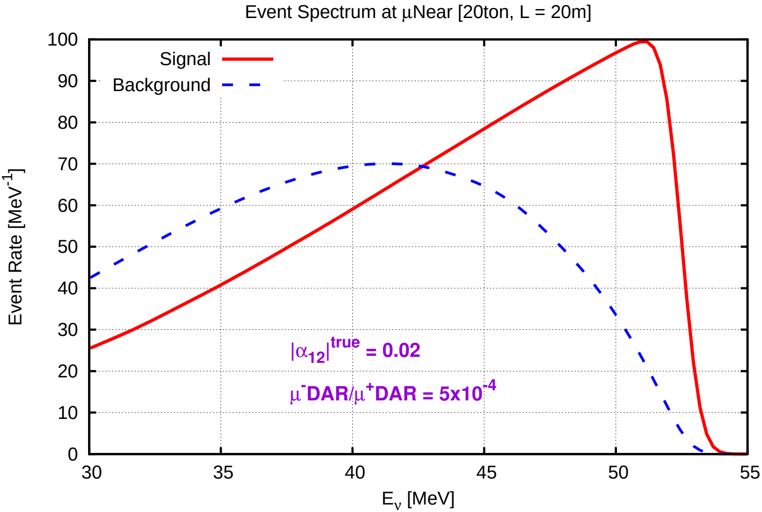
$$P^{NP}_{\mu e} = \alpha^2_{11} \left\{ \alpha^2_{22} \left[c^2_a |S'_{12}|^2 + s^2_a |S'_{13}|^2 + 2 c_a s_a (\cos \delta_D \mathbb{R} - \sin \delta_D \mathbb{I})(S'_{12} S'^*_{13}) \right] + |\alpha_{21}|^2 P_{ee} \right.$$
$$\left. + 2 \alpha_{22} |\alpha_{21}| \left[c_a \left(c_\phi \mathbb{R} - s_\phi \mathbb{I} \right) \left(S'_{11} S'^*_{12} \right) + s_a \left(c_{\phi + \delta_D} \mathbb{R} - s_{\phi + \delta_D} \mathbb{I} \right) \left(S'_{11} S'^*_{13} \right) \right] \right\} \,.$$



μNear at μDAR

Ge, Pasquini, Tortola & Valle [1605.01670]

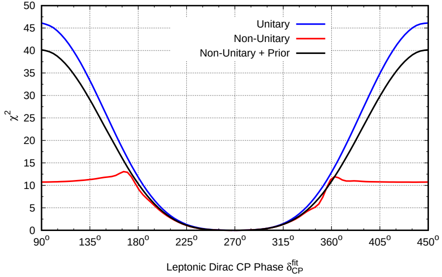
$$P^{NP}_{\mu e}(L \to 0) = \alpha^2_{11}|\alpha_{21}|^2 P_{ee} \approx \alpha^2_{11}|\alpha_{21}|^2 \approx |\alpha_{21}|^2$$



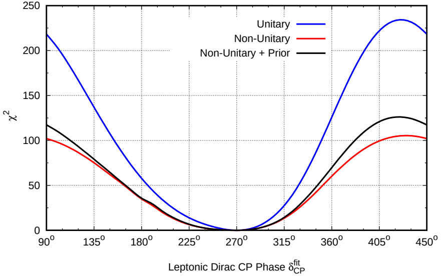
TNT2K+μNear

Ge, Pasquini, Tortola & Valle [1605.01670]

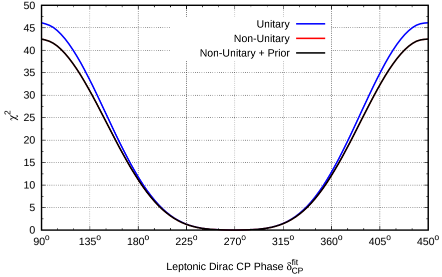
The effect of including non-unitarity at T2K+μSK [δ_{CP}^{true}= -90^o, NH]



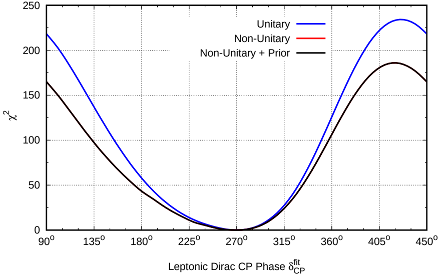
The effect of including non-unitarity at T2HK+μHK [δ_{CP}^{true}= -90^o, NH]



The effect of including non-unitarity at T2K+μSK+μNear [δ_{CP}^{true}= -90^o, NH]



The effect of including non-unitarity at T2HK+μHK+μNear [δ_{CP}^{true}= -90^o, NH]



Non-Standard Interaction

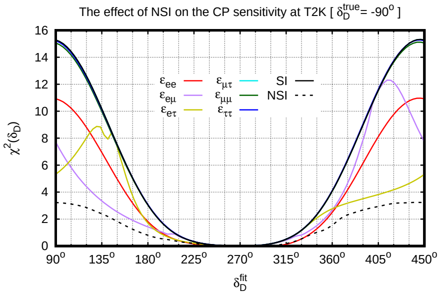
SFG & Alexei Smirnov [arXiv:1607.08513]

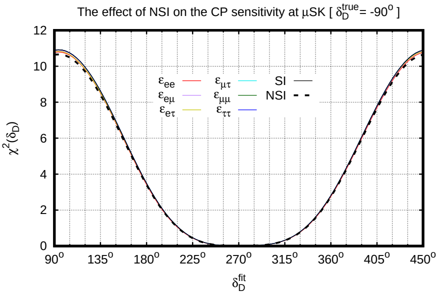
$$\mathcal{H} \equiv \frac{1}{2\mathbf{E}_\nu} U \begin{pmatrix} 0 & & \\ & \Delta m_s^2 & \\ & & \Delta m_a^2 \end{pmatrix} U^\dagger + V_{cc} \begin{pmatrix} 1 + \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix}$$

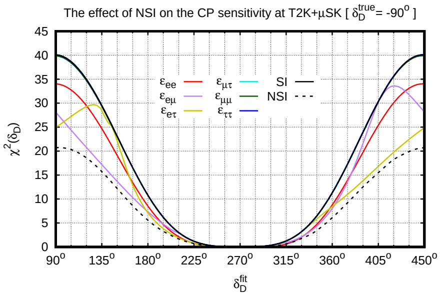
- Standard Interaction – V_{cc} (also V_{nc})
- Non-Standard Interaction – $\epsilon_{\alpha\beta}$
  - **Diagonal $\epsilon_{\alpha\alpha}$ are real**
  - **Off-diagonal $\epsilon_{\alpha\neq\beta}$ are complex**
  - **Both can fake CP**
- Z' in LMA-Dark model with $L_\mu - L_\tau$ gauged as $U(1)$
  - $M_{Z'} \sim \mathcal{O}(10)$MeV
  - $g_{Z'} \sim 10^{-5}$

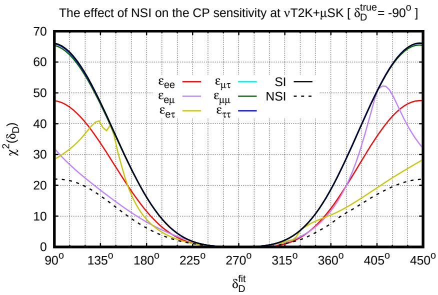
CP Sensitivity at T2K & μSK

SFG & Alexei Smirnov [arXiv:1607.08513]


The effect of NSI on the CP sensitivity at T2K [δ_D^{true}= -90^o]


The effect of NSI on the CP sensitivity at µSK [δ_D^{true}= -90^o]


The effect of NSI on the CP sensitivity at T2K+µSK [δ_D^{true}= -90^o]


The effect of NSI on the CP sensitivity at νT2K+µSK [δ_D^{true}= -90^o]

Scalar NSI

SFG & Stephen Parke, Phys.Rev.Lett. **122** (2019) no.21, 211801 [1812.08376]

- **Vector NSI**

$$\mathcal{L}^{\text{eff}}_{\text{cc}} = \frac{g_{\alpha\rho} g^*_{\beta\sigma}}{2} \frac{1}{-m^2_V} \left(\overline{\nu_\alpha} \gamma_\mu P_L \nu_\beta\right) \left(\bar{\ell}_\sigma \gamma^\mu P_L \ell_\rho\right) \ ,$$

  which is **vector-vector type vertex**.

- **Scalar Mediator**

$$-\mathcal{L} = \frac{1}{2} m^2_\phi \phi^2 + \frac{1}{2} M_{\alpha\beta} \bar{\nu}_\alpha \nu_\beta + y_{\alpha\beta} \phi \bar{\nu}_\alpha \nu_\beta + Y_{\alpha\beta} \phi \bar{f}_\alpha f_\beta + h.c. \,,$$

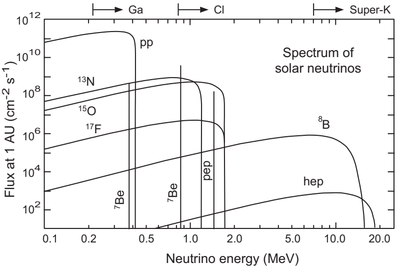
  Due to **forward scattering**, the **effective Lagrangian** is

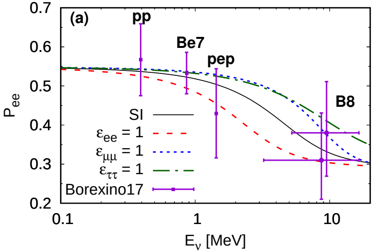
$$\mathcal{L}^s_{\text{eff}} \propto y_{\alpha\beta} Y_{ee} \left[\bar{\nu}_\alpha(p_3) \nu_\beta(p_2)\right] \left[\bar{e}(p_1) e(p_4)\right] \ ,$$

  which is a **scalar-scalar type vertex** ⇒ **significant phenomenological consequences**.

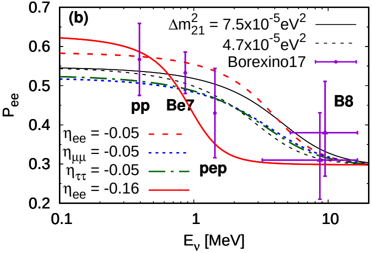
$$\mathcal{H} \approx E_\nu + \frac{(M + \mathbf{M_S})(M + \mathbf{M_S})^\dagger}{2E_\nu} \pm V_{\text{SI}} \,,$$

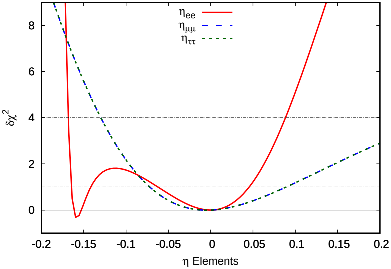
Solar Neutrino



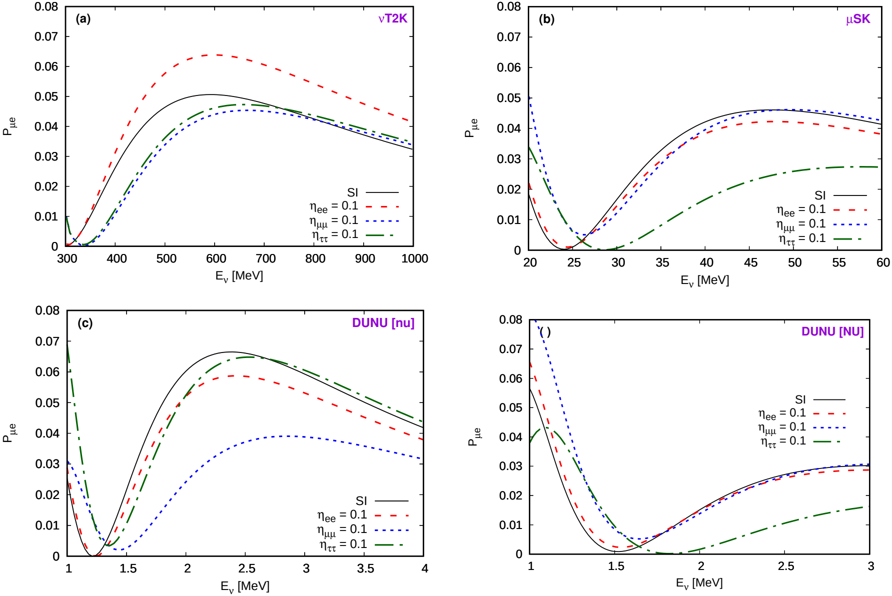


$$\mathbf{P}_{\mathbf{ee}}^{\mathrm{sun}} = \left|\mathbf{U}_{\mathbf{ei}}^{\mathrm{prod}}(\mathbf{U}_{\mathbf{ei}}^{\mathrm{vac}})^*\right|^2$$





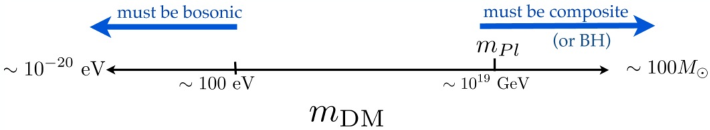
Scalar NSI @ Accelerator Neutrino Oscillation



Light Dark Matter

SFG, Hitoshi Murayama [arXiv:1904.02518]

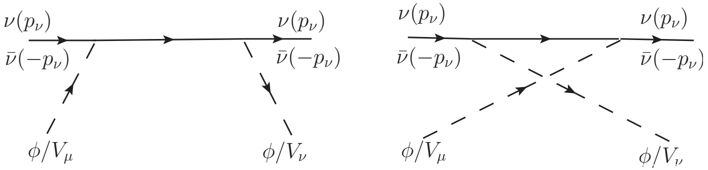
- **The DM mass can span almost 100 orders**



- For **light bosonic DM**

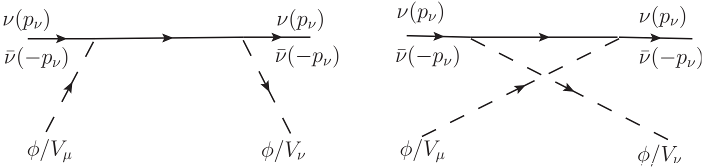
$$-\mathcal{L} = \frac{1}{2} m_\phi^2 \phi^2 + \frac{1}{2} M_{\alpha\beta} \bar{\nu}_\alpha \nu_\beta + y_{\alpha\beta} \phi \bar{\nu}_\alpha \nu_\beta + h.c.\,,$$

leading to **forward scattering**



Effective Mass Correction from Dark Matter

- The **forward scattering** with the **DM background**



- modifies the neutrino **kinetic term**

$$i\delta\Gamma_{\alpha\beta} = \frac{i\rho_\phi(\mathbf{v}_\phi)}{m_\phi^2}\sum_j y_{\alpha j} y^*_{j\beta}\left[\frac{\not p_\nu + \not \mathbf{p}_\phi + m_\nu}{p_\phi^2 + \mathbf{2p}_\nu\cdot\mathbf{p}_\phi} + \frac{\not p_\nu - \not \mathbf{p}_\phi + m_\nu}{p_\phi^2 - \mathbf{2p}_\nu\cdot\mathbf{p}_\phi}\right]$$

with $\mathbf{p}_\phi \sim \mathbf{m}_\phi(\mathbf{1}, \tilde{\mathbf{v}}_\phi)$, the correction

$$\boldsymbol{\delta\Gamma}_{\alpha\beta} \approx \sum_j y_{\alpha j} y^*_{j\beta}\frac{\rho_\chi}{m_\phi^2 \mathbf{E}_\nu}\gamma_0$$

appears as **dark potential**.

SFG, Hitoshi Murayama [arXiv:1904.02518]

Dark NSI

SFG, Hitoshi Murayama [arXiv:1904.02518]

- The **dark potential**

$$\boldsymbol{\delta\Gamma}_{\alpha\beta} \approx \sum_j y_{\alpha j} y^*_{j\beta} \frac{\rho_\chi}{m_\phi^2 \mathbf{E}_\nu} \gamma_0$$

is a correction to the Hamiltonian, same as the matter potential.

- Due to $1/E_\nu$ **dependence**, the **dark potential** is promoted to mass correction

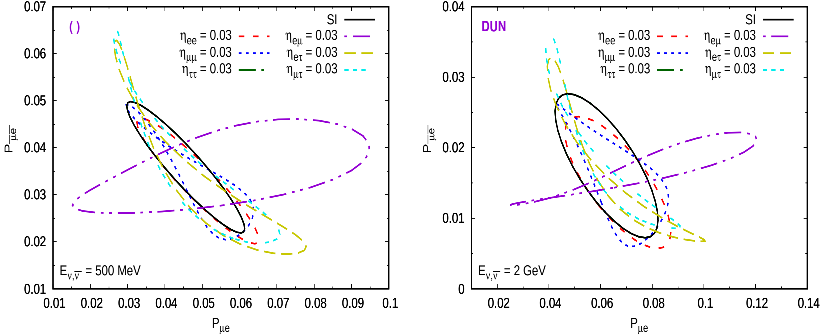
$$H = \frac{M^2}{2E_\nu} - \frac{1}{\mathbf{E}_\nu} \sum_j y_{\alpha j} y^*_{j\beta} \frac{\rho_\chi}{m_\phi^2} \equiv \frac{M^2 + \boldsymbol{\delta}\mathbf{M}^2}{2\mathbf{E}_\nu}$$

which is totally different from the scalar NSI.

- **With mass term correction, any neutrino oscillation cannot see the original variables. Neutrino oscillation can happen even if the original mass term M^2 vanishes.**

Dark NSI & Faked CP

- With just 3% of dark NSI



- The biprobability contour can totally change.

SFG, Hitoshi Murayama [arXiv:1904.02518]

Summary

- **Better CP measurement than T2K**
  - Much larger event numbers
  - Much better CP sensitivity around maximal CP
  - Solve degeneracy between δ_D & $\pi - \delta_D$
  - Guarantee CP sensitivity against NUM
  - Guarantee CP sensitivity against NSI (vector, scalar, dark)
- **Better configuration than DAEδALUS**
  - Only one cyclotron
  - 100% duty factor
  - Much lower flux intensity
  - Much easier
  - Much cheaper
  - Single near detector

Thank You!

LHC & Daya Bay changed Physics in 2012

- **Higgs boson** ⇒ electroweak symmetry breaking & mass.
- **Chiral symmetry breaking** ⇒ majority of mass.
- **The world seems not affected by the tiny neutrino mass?**
    - Neutrino mass ⇒ Mixing
    - 3 Neutrino ⇒ possible **CP violation**
    - CP violation ⇒ **Leptogenesis**
    - **Leptogenesis** ⇒ **Matter-Antimatter Asymmetry**
    - There is something left in the Universe.
    - Baryogenesis from quark mixing is not enough.
- Majorana ν ⇔ **Lepton Number Violation**
- **Residual $\mathbb{Z}_2$ Symmetries:** $\cos \boldsymbol{\delta_{\mathrm{D}}} = \frac{(s_s^2 - c_s^2 s_r^2)(\mathbf{c}_{\mathbf{a}}^2 - \mathbf{s}_{\mathbf{a}}^2)}{4 c_a s_a c_s s_s \mathbf{s}_{\mathbf{r}}}$ 1108.0964 1104.0602

ν Oscillation Data

(for NH)	-1σ	Best Value	$+1\sigma$
$\boldsymbol{\Delta m^2_s} \equiv \Delta m^2_{12}\,(\mathbf{10^{-5}}\mathrm{eV}^{\mathbf{2}})$	7.37	**7.56**	7.75
$\left\lvert \boldsymbol{\Delta m^2_a} \equiv \Delta m^2_{13} \right\rvert\,(\mathbf{10^{-3}}\mathrm{eV}^{\mathbf{2}})$	2.51	**2.55**	2.59
$\sin^2 \boldsymbol{\theta_s}\ (\boldsymbol{\theta_s} \equiv \boldsymbol{\theta_{12}})$	0.305 (33.5°)	0.321 (**34.5°**)	0.339 (35.6°)
$\sin^2 \boldsymbol{\theta_a}\ (\boldsymbol{\theta_a} \equiv \boldsymbol{\theta_{23}})$	0.412 (39.9°)	0.430 (**41.0°**)	0.450 (42.1°)
$\sin^2 \boldsymbol{\theta_r}\ (\boldsymbol{\theta_r} \equiv \boldsymbol{\theta_{13}})$	0.02080 (8.29°)	0.02155 (**8.44°**)	0.02245 (8.62°)
$\delta_{\mathrm{D}}, \delta_{\mathrm{Mi}}$	?, **??**	?, **??**	?, **??**

Salas, Forero, Ternes, Tortola & Valle, arXiv:1708.01186

The Dirac CP Phase δ_D @ Accelerator Exp

- To leading order in $\alpha = \frac{\delta M^2_{21}}{|\delta M^2_{31}|} \sim 3\%$, the oscillation probability relevant to measuring δ_D @ **T2(H)K**,

$$P_{\substack{\nu_\mu\to\nu_e \\ \overline{\nu}_\mu\to\overline{\nu}_e}} \approx 4 s_a^2 c_r^2 s_r^2 \sin^2\phi_{31} - 8 c_a s_a c_r^2 s_r c_s s_s \sin\phi_{21} \sin\phi_{31} \left[\cos\delta_D \cos\phi_{31} \pm \sin\delta_D \sin\phi_{31}\right]$$

for ν & $\overline{\nu}$, respectively. $[\phi_{ij} \equiv \frac{\delta m^2_{ij} L}{4E_\nu}]$

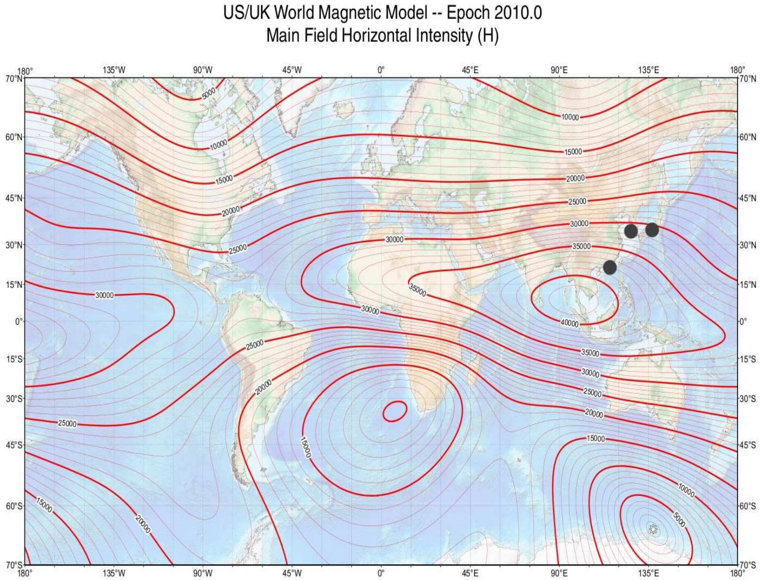
- $\nu_\mu \to \nu_\mu$ Exps measure $\sin^2(2\theta_a)$ precisely, but not $\sin^2\theta_a$.

- Run both ν & $\overline{\nu}$ modes @ first peak $[\phi_{31} = \frac{\pi}{2}, \phi_{21} = \alpha\frac{\pi}{2}]$,

$$P_{\overline{\nu}_\mu\to\overline{\nu}_e} + P_{\nu_\mu\to\nu_e} = 2 s_a^2 c_r^2 s_r^2 ,$$

$$P_{\overline{\nu}_\mu\to\overline{\nu}_e} - P_{\nu_\mu\to\nu_e} = \alpha\pi \sin(2\theta_s)\sin(2\theta_r)\sin(2\theta_a)\cos\theta_r \sin\delta_D .$$

Lowest Atmospheric Neutrino Background



Backgrounds to IBD ($\overline{\nu}_e + p \rightarrow e^+ + n$)

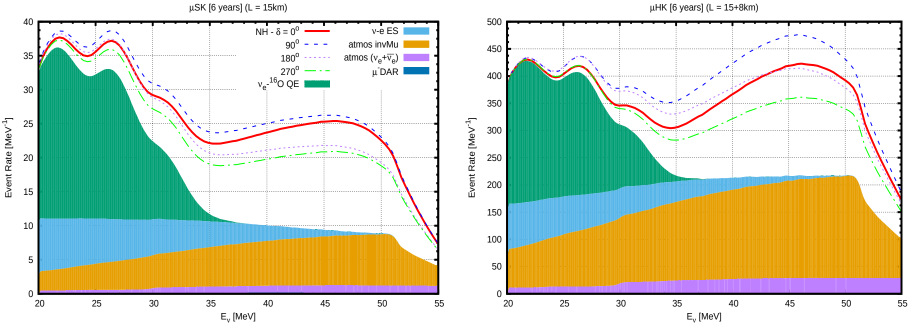
- Reactor $\overline{\nu}_e$: $E_\nu < 10$ MeV
- Accelerator ν_e: $E_\nu > 100$ MeV
- Spallation: $E_\nu \lesssim 20$ MeV
- Supernova Relic Neutrino: $E_\nu \lesssim 20$ MeV

Cut with $30 \text{ MeV} < E_\nu < 55$ MeV

- Accelerator $\nu_\mu \rightarrow$ **Invisible muon**
- Atmospheric Neutrino Background
  - **Invisible muon** (below Cherenkov limit)
    - $E_\mu \lesssim 1.5 \times m_\mu$, $\mu^\pm \rightarrow e^\pm$
    - $E_\pi \lesssim 1.5 \times m_\pi$, $\pi^+ \rightarrow \mu^+ \rightarrow e^+$
    - 1 neutron
    - No prompt photon
  - Irreducible $\overline{\nu}_e$: $30 \text{ MeV} \lesssim E_\nu \lesssim 55$ MeV
  - Reducible ν_e: $60 \text{ MeV} \lesssim E_\nu \lesssim 100$ MeV
    - 1 neutron
    - No prompt photon
  - **Lowest** at μDARTS & TNT2K sites

Event Shape @ TNT2K

Evslin, Ge & Hagiwara [1506.05023]



Expected μDAR IBD signal from 6 yrs of running @ SK (15km) & HK (23km) with NH.

Simulated by **NuPro**, http://nupro.hepforge.org/

NUM vs Seesaw Mechanism

- **Heavy neutrinos**

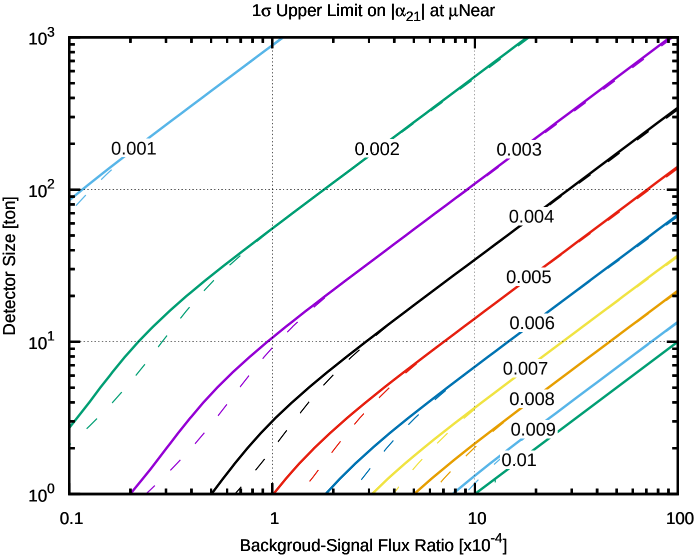
$$\bar{\nu} M_D \mathcal{N} + h.c. + \overline{\mathcal{N}} M_N \mathcal{N} = \begin{pmatrix} \bar{\nu} & \overline{\mathcal{N}} \end{pmatrix} \begin{pmatrix} 0 & M_D \\ M_D^T & M_N \end{pmatrix} \begin{pmatrix} \nu \\ \mathcal{N} \end{pmatrix}$$

- **Seeaw Mechanism**

$$M_\nu = -M_D M_N^{-1} M_D^T \,, \qquad \nu' = \nu + M_D M_N^{-1} \mathcal{N}$$

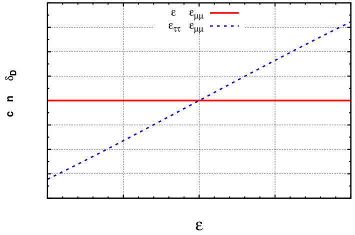
μNear at μDAR

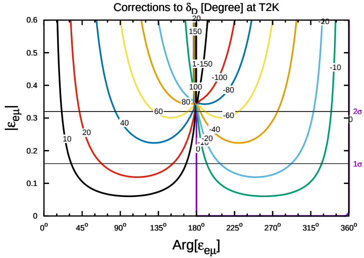
Ge, Pasquini, Tortola & Valle [1605.01670]

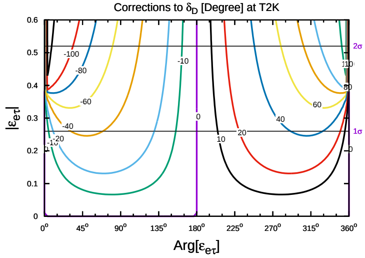


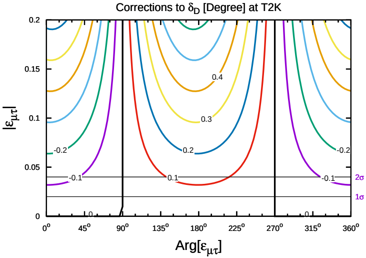
Faked CP with NSI

SFG & Alexei Smirnov [arXiv:1607.08513]




Corrections to δ_D [Degree] at T2K


Corrections to δ_D [Degree] at T2K


Corrections to δ_D [Degree] at T2K

EOM & Effective Hamiltonian with Scalar NSI

- **Two-Point Correlation Function**

$$\begin{aligned}\delta\Gamma_S &= \frac{y_{\alpha'\beta'}y_{ee}}{m_\phi^2}\langle\nu_\alpha|\bar\nu_{\alpha'}\nu_{\beta'}|\nu_\beta\rangle\langle e|\bar e e|e\rangle\,,\\ \delta\overline{\Gamma}_S &= \frac{y_{\beta'\alpha'}y_{ee}}{m_\phi^2}\langle\bar\nu_\alpha|\bar\nu_{\alpha'}\nu_{\beta'}|\bar\nu_\beta\rangle\langle e|\bar e e|e\rangle\,.\end{aligned}$$

- **Equation of Motion**

$$\bar\nu_\beta\left[i\partial_\mu\gamma^\mu + \left(M_{\beta\alpha} + \frac{n_e y_e Y_{\alpha\beta}}{m_\phi^2}\right)\right]\nu_\alpha = 0\,,$$

- **Effective Hamiltonian**

$$\mathcal{H} \approx E_\nu + \frac{(M+M_S)(M+M_S)^\dagger}{2E_\nu} \pm V_{\rm SI}\,,$$

Mass Scale & Unphysical CP Phases in Oscillation

- The **effective mass term** is a combination

$$\mathbf{M}\mathbf{M}^\dagger \to (\mathbf{M} + \mathbf{M_S})(\mathbf{M} + \mathbf{M_S})^\dagger = \mathbf{M}\mathbf{M}^\dagger + \mathbf{M}\mathbf{M}_\mathbf{S}^\dagger + \mathbf{M_S}\mathbf{M}^\dagger + \mathbf{M_S}\mathbf{M}_\mathbf{S}^\dagger$$

- The **absolute neutrino mass** can enter neutrino oscillation!

$$\mathbf{M}\mathbf{M}_\mathbf{S}^\dagger + \mathbf{M_S}\mathbf{M}^\dagger$$

- The **unphysical CP phases** can also enter neutrino oscillation!

$$M \equiv R_\nu D_\nu R_\nu^\dagger \quad \& \quad R_\nu \equiv P_\nu U_\nu Q_\nu$$

The **Majorana rephasing matrice** $Q_\nu = \{e^{i\delta_{\mathrm{M1}}/2}, 1, e^{i\delta_{\mathrm{M3}}/2}\}$ can be absorbed, $Q_\nu D_\nu Q_\nu^\dagger = D_\nu$ while the **unphysical rephasing matrix** $P_\nu \equiv \{e^{i\alpha}, e^{i\beta}, e^{i\gamma}\}$ can not be simply rotated away now:

$$M \to \widetilde{\mathbf{M}} = \mathbf{U}_\nu \mathbf{D}_\nu \mathbf{U}_\nu^\dagger\,, \qquad M_S \to \widetilde{\mathbf{M}}_\mathbf{S} = \mathbf{P}_\nu^\dagger \mathbf{M_S} \mathbf{P}_\nu$$

Parametrization & Constant Density Subtraction

- Use **characteristic scale $\mathbf{\Delta m_a^2}$** to parametrize scalar NSI

$$\widetilde{\mathbf{M}}_{\mathbf{S}} \equiv \sqrt{\mathbf{\Delta m_a^2}} \begin{pmatrix} \eta_{ee} & \eta^*_{\mu e} & \eta^*_{\tau e} \\ \eta_{\mu e} & \eta_{\mu\mu} & \eta^*_{\tau\mu} \\ \eta_{\tau e} & \eta_{\tau\mu} & \eta_{\tau\tau} \end{pmatrix},$$

  where $\mathbf{\Delta m_a^2} \equiv \Delta m^2_{31} = 2.7 \times 10^{-3}\,\mathrm{eV}^2$.

- We first need **input** for $\widetilde{\mathbf{M}}$ which is not directly measured.

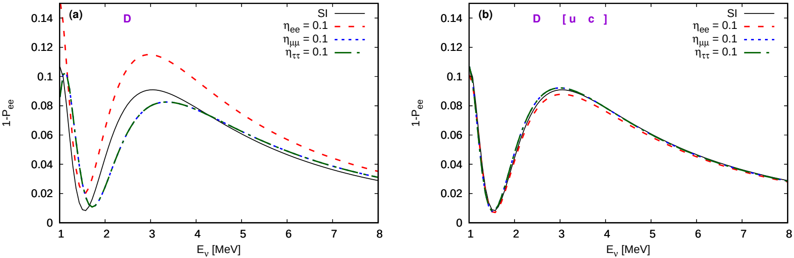
- However, the directly measured from terrestial experiments is always a combination, $\widetilde{\mathbf{M}} + \widetilde{\mathbf{M}}_{\mathbf{S}}(\rho_{\mathbf{s}} \approx \mathbf{3}\mathrm{g/cm}^{\mathbf{3}})$. It is then necessary to first substract a constant term:

$$\widetilde{M} \to \widetilde{M} + \widetilde{\mathbf{M}}_{\mathbf{S}} \frac{\rho - \rho_{\mathbf{s}}}{\rho_{\mathbf{s}}}$$

  where $\widetilde{\mathbf{M}} = \mathbf{U}_\nu \mathbf{D}_\nu \mathbf{U}_\nu^\dagger$ is **reconstructed** in terms of the measured mixing matrix while $\widetilde{M}_S$ is the scalar NSI @ typical constant **subtraction density $\rho_{\mathbf{s}}$**.

Density Subtraction for Reactor Anti-Neutrinos

- Since the reactor anti-neutrino experiments (**Daya Bay** & **JUNO**) are the most precise ones, we do substraction according to them:



$$\widetilde{M} \to \widetilde{M} + \widetilde{\mathbf{M}}_{\mathbf{S}} \frac{\rho - \rho_{\mathbf{s}}}{\rho_{\mathbf{s}}}$$

- Then **no constraint** on **scalar NSI** from reactor experiments!

Scalar NSI @ Atmospheric Neutrino Oscillation